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A METHOD FOR EVALUATING SO2 ABATEMENT STRATEGIES

MONSANTO RESEARCH CORPORATION

PREPARED FOR
INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY

SEPTEMBER 1975

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16. ABSTRACT The report describes a non-deterministic probabilistic method that can be used to evaluate sulfur oxides abatement alternatives. The method is not restricted to gas scrubbing models, but can also handle clean fuel substitution processes. The method utilizes a Monte Carlo simulation approach which can treat fully developed cost models and also those which encompass a high level of uncertainty either in structure or in process parameters. The report presents impact assessment techniques which can be used to develop methodology for alternative future scenarios. A specific example, the Wellman-Allied process, is used to demonstrate the utility of simulation methodology.

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FOR EVALUATING

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by

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ABSTRACT

A non-deterministic, probabilistic methodology has been developed as an aid to the EPA decision maker when evaluating sulfur oxides abatement alternatives. This methodology is not restricted to gas scrubbing models and can handle clean fuel substitution processes. A Monte Carlo Simulation approach is described which can treat fully developed cost models and also those which encompass a high level of uncertainty either in structure or process parameters. Impact Assessment techniques are presented which develop the methodology of alternative future scenarios. A specific example, the Wellman-Allied Process, is used to demonstrate the utility of this simulation methodology.

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SECTION I

SUMMARY

We have developed a methodology for evaluating pollution abatement and clean fuel alternatives in a well-traceable, systematic fashion. Employing a combination of classical engineering economics and process analysis together with the disciplines of decision analysis and impact assessment, we present a practical, flexible technique as a utilitarian aid to the decision maker.

Several novel approaches were used to overcome previous difficulties encountered when using a deterministic approach. When dealing with future projections on any variable, we are faced with uncertainty. To deal with the many complexities inherent in this situation, we first applied the impact assessment approach - a method that presents, in a readily traceable fashion, techniques useful in developing future scenarios.

Having developed a rationale for treating the future, we then developed quantitative methods for treating uncertainty. These techniques include the use of statistical inputs and the use of simulation to produce statistical results.

Comparison of clean fuel alternatives with flue gas scrubbing has presented conceptual as well as computational problems. An innovative approach was used to allow a common basis of comparison. This required the inclusion of the cost of coal and the transportation distance from the mine mouth to the using site.

In addition, we have shown how this methodology can take into account the uncertainties in any step of an ill-defined (because of the lack of experimental data) process, both in the cost of equipment and in the operating cost, and to allow for projections to a fully commercialized process.

The job of allocating R&D funds for SO_x pollution abatement in an optimum manner, so as to minimize the future total cost for SO_x abatement in the U.S., is made difficult by the rapid changes in energy availability, national regulations, and economic growth. This versatile methodology was designed to assist the Control Systems Laboratory in allocating these funds in light of these changes.

This system can, over a period of time, answer an increasingly widening series of questions such as:

1. At what level of sludge disposal costs do regenerable processes become preferable?
2. How will fuel availability and cost affect the allocation process?
3. How will the future growth of utilities and industries affect the relative merits of candidate alternatives?

4. How should low sulfur coal be compared to flue gas cleaning and how do we model the attitudes of utility and industry representatives?
5. How do transportation costs affect the relative merits of the alternatives?

This program and resulting models are modular and quick in response. Because of their flexible nature the programs will be able to treat unexpected rapid developments in a very orderly framework and a convenient well-defined manner.

SECTION II

INTRODUCTION

A. PREVIOUS WORK

The objective of this work was to develop a methodology for evaluating alternatives for sulfur oxides abatement. This methodology has been developed, and should be helpful in assessing the economics of various competitive methods. A great deal of valuable information was gathered by M. W. Kellogg personnel (EPA Contract 68-02-1303)[1] both on emission sources and on cost models for four specific processes for SO_x abatement. A problem arose, however, when attempts were made to use the equations to calculate the costs of control for large groups of SO_x sources, such as all coal-fired power plants or all coal-fired industrial boilers in the U.S.

Further problems arise when one considers the future. It is probable that more power plants will be needed to fulfill the ever-rising power demand in the U.S. It is hard to be specific, however, about where plants will be built in the year 1980; for example, how much will the demand increase in southern Ohio? Will the plants that are needed to supply this additional capacity be built in southern Ohio, or will they be built in Kentucky and the power transmitted to Ohio over high tension, long distance transmission wires?

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What will be the availability of sludge disposal areas near these plants, whose number, size, and location are at present unknown?

The amount of specific information needed to apply this "deterministic" approach and the impossibility of obtaining this information for future plants make this approach almost impossible to apply even to one small region, much less the whole U.S. Even if some method could be found to obtain the necessary information, the volume of data needed for each specific power plant multiplied by the total number of coal-fired power plants would require extensive data processing facilities and complex data management procedures.

As inputs to this study, attempts were made to define the future demand for electric power in the U.S. and future expected development costs and operating costs for a number of SO_x abatement processes by means of the Delphi technique. Panels of experts were convened to comment on detailed questionnaires which had been filled out by these consultants. A large amount of information was compiled from these questionnaires and meetings; however, the difficulties in applying this information to a plant-by-plant calculation still remained.

Facing the uncertainties as to how to further proceed, Monsanto Research Corporation (MRC) was assigned the task (under EPA Contract 68-02-1320, Task 5) of developing an approach which could be used to evaluate alternative costs for SO_x abatement. During this work a new approach was generated, in which plants would be considered in

large groups rather than individually. Since it is known that all plants have different cost factors, the differences in wage rates at different plants were taken into account by using a distribution of wage rates rather than one specific value. Difficult calculations, such as costs to haul sludge from the limestone scrubbing process to available landfill sites, are avoided by summarizing sludge disposal costs as a distribution function. As long as the distribution function represents the costs of sludge disposal reasonably well over the average of many plants, manipulation of these data by simulation techniques leads to reasonable overall estimates.

There is a large number of variables that are used to calculate operating costs for SO_x abatement processes. Some of these variables have a much larger effect on the operating costs than others. We performed sensitivity analyses on the input variables to determine which ones had the most significant effect. Variables, such as the percent of ash in coal, which would not be expected to have a large effect on the calculated results, were entered as specific values. Variables which would significantly affect the costs were treated as distribution functions.

Having developed this new approach to this problem, MRC was then asked to develop this concept into a practical application for evaluating national SO_x abatement alternatives. Drawing heaviliy upon previous work by M. W. Kellogg, MRC personnel assembled cost models for the Limestone scrubbing, Wellman-Allied, Lurgi Synthetic

Natural Gas, and Solvent Refined Coal processes into several computer programs. Input data on sizes of power plants, and their load factors were also drawn from previous work. Using these equations we performed sensitivity analyses on the variables and determined which one needed to be used as a distribution function. Distribution functions have been compiled for key variables. Based upon numerous specific assumed values for variables, costs for national SO_x abatement using these four specific processes were calculated as examples of how this method might be used in the future.

The sample results calculated using the methodology developed in this work are strongly a function of assumed input variables. This should prove helpful since it means the possible economic effects of making changes in numerous variables can be quickly investigated. This also means, however, that one should beware of merely abstracting values from this work and using them in an unquestioning fashion as being the actual costs which will prevail for a specific process in 1980, since many of the values were for test purposes only and may not be correct. One must verify that the values for input variables are in accord with best estimates currently available before using the reported values. This work was done to establish the method, not to produce guaranteed cost figures.

In this work, the probabilistic method for analyzing future SO_x abatement costs has been developed. Equations for specific processes have been combined with values of input variables for coal-fired electric utility boilers,

industrial boilers, sulfuric acid plants, and sulfur recovery plants. Classes of SO_x sources and annual SO_x abatement costs for these plants have been simulated. This system should be useful in testing the effect of different values of input variables on expected SO_x abatement costs. It should also be useful in helping to determine what effect process improvements or development of a new SO_x abatement process would have on future expected costs.

SECTION III

PROBABILISTIC APPROACH

One approach that would answer questions on R&D fund allocation would be to assemble a set of equations that could be solved to give one unique answer for a set of basic assumptions. By assuming rational, best estimates on variables such as fuel cost, labor cost, by-product cost, transportation cost and interest rates, one would then be able to calculate a unique value of national cost for SO_x abatement for the processes available. A model of this type is called deterministic because it enables a specific, unique solution to be determined.

A significant problem arises, however, in using this type of approach. Because the future is always uncertain, the appropriate values to use for given variables are unknown. What will be the price of coal in 1980? What interest rates will prevail at the time someone wishes to build a new plant for SO_x abatement or the production of clean fuel? We know these costs will change with time.

The deterministic approach when applied to processes strongly influenced by future variables, as is the case of R&D allocation, encounters severe uncertainties. To intelligently assess events in 1980, a range of values

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for futuristic variables such as the price of coal must be considered. A minimum of two values would have to be selected for each deterministic future variable in order to determine its effects and interactions with other variables. With a deterministic model containing 20 variables at 2 values each, we would calculate 2^{20} or over 1 million results for national SO_x abatement costs.

These results would be difficult to analyze, and the relative probability that any one of these values was better than another would be unspecified. Hence, a selection of the most probably value of these 1 million results would not be possible. We present an alternative approach that avoids this situation.

If we describe the inputs as statistical distributions then by performing a probabilistic simulation, any desired output variable can be plotted to form on probability distribution curve. This curve may consist of cost/unit energy for a given alternative on the abscissa and the probabilities from 0 to 1.0 on the ordinate. At the 0.5 probability point on the curve, a unique value of cost can be read. This procedure also has another advantage - it describes the range of uncertainty on the obtained results.

The approach of assigning probability values to futuristic variables rather than giving them predetermined values will be referred to as the probabilistic approach. It has the advantage of reducing the complexity

of the problem to manageable bounds and it also defines the uncertainty in the values calculated. This method is well founded in the science of decision analysis and probabilistic simulation.

Our final thought on the probabilistic approach is best expressed by quoting from a letter dated July 26, 1967, written by Robert E. Pfenning, Vice President and Comptroller of the General Electric Company. The letter was addressed to all of General Electric's department general managers and managers of finance, and it marked an unprecedented change in policy. It read in part as follows: " . . . Conventional budgets and forecasts present single value data as expressions of business plans, yet the very nature of the planning process involves conditions of uncertainty which are better communicated using probabilities, ranges of values, and expected values. . . "

SECTION IV

SIMULATION METHODOLOGY

The deterministic approach is straight-forward, using single valued information and computing a single result. When statistical distributions are used as inputs, statistical mathematics must be applied. Many of these mathematical approaches are extremely complex even when dealing with the simple Gaussian or Normal distribution. When the inputs are not Normally distributed there are no known analytical techniques that can be applied. We must turn then to a process called probabilistic simulation or "Monte Carlo analysis."

The expression "Monte Carlo analysis" was coined by two mathematicians, John von Neumann and S. Ulam, in the late 1940's to describe a mathematical technique. They developed this technique while working on problems concerning the shielding of nuclear devices which they found to be too complicated to treat analytically and too expensive and risky to solve by physical experimentation. The name they chose seems appropriate enough since the basic principle is the same as one finds in the operation of casinos at Monaco. Devices are used there which produce random samples from well defined populations.

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In the present case, however, the device that we use is the electronic digital computer. The Monte Carlo method really refers to a collection of techniques invented to solve a number of different types of problems. In this collection can be found a common idea which serves to bind the techniques together. This is the notion of approximating the solution to a problem by sampling from various processes. Thus, instead of using one value for the amount of sulfur in coal, we use a distribution of values for sulfur in coal. Or, as in the case of the location cost factor, we have a distribution of cost factors for various cities in the United States. The same holds true for other critical variables, such as the price of coal. This is not an experimentally derived distribution but one that is projected on the basis impact analytic techniques and encoding of uncertainty methodology.[2]

SECTION V

DECISION ANALYTIC APPROACH

The questions that might be asked will mainly deal with future events. Because of this, a degree of uncertainty is inherent. Because of this very important fact, we have chosen elements from a methodology that is ideally suited for cases where probabilistic statements will be the rule rather than the exception. This methodology is decision analysis. Decision analysis can be described as a merger of the two fields of decision theory and systems analysis. Decision theory provides the philosophy for logical behavior in decision situations constrained by uncertainty. Systems analysis as used here represents systems and modeling methodology that captures the interactions and dynamics of complex problems. Combining the two results in a theory and methodology that allows analysis of complex, dynamic, and uncertain decision situations.[2] We will describe how decision analysis can be used to attack this particular decision problem.

The decision analysis cycle can be summarized as follows (see Figure 1). It is made up of three distinct phases:[3]

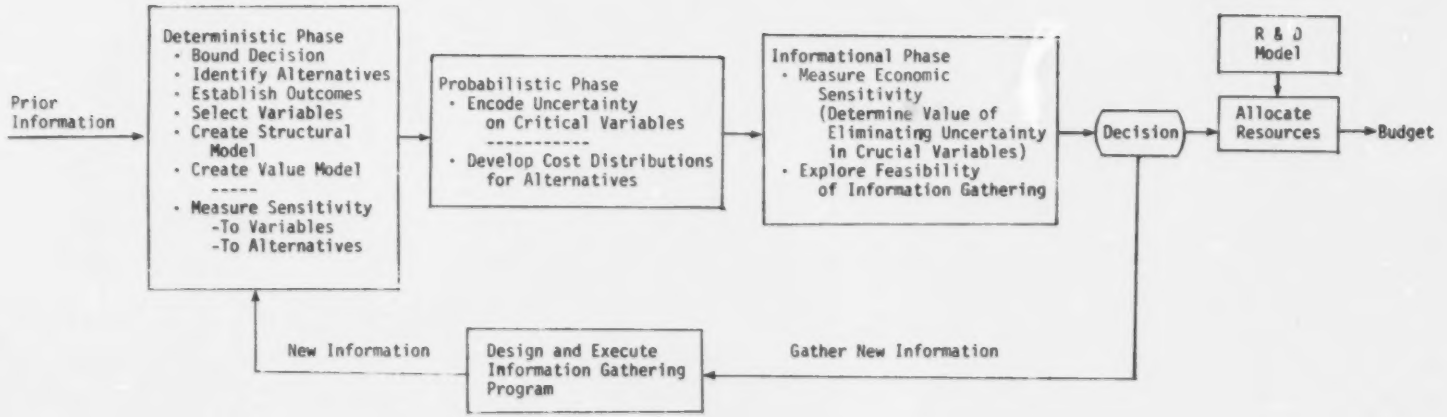

Figure 1. The SO_2 systems analysis program in a decision analysis framework

(1) deterministic
(2) probabilistic
(3) informational

The deterministic phase is concerned with the basic structuring of the problem. The structuring entails defining relevant variables, characterizing their relationships in formal models, and assigning values to possible outcomes. The importance of the different variables is measured through sensitivity analysis.

In the probabilistic phase uncertainty is explicitly incorporated by assigning probability distributions to the critical variables. These distributions are transformed in the models that exhibit the uncertainty in the final outcome, which again is represented by a probability distribution. We can then quantitatively rank the alternatives in the face of uncertainty.

The informational phase determines the economic value of information by calculating the worth of reducing uncertainty in each of the important variables in the problem. The value of additional information can then be compared with the cost of obtaining it.

If the gathering of information is profitable, the three phases are repeated again. The analysis is completed when further analysis or information gathering is no longer profitable.

A. THE DETERMINISTIC PHASE

The basic steps of the deterministic phase are as follows:

(1) Bound the decision
(2) Identify the alternatives
(3) Establish the outcome
(4) Select the decision variables and the state variables
(5) Create a structural model
(6) Create a value model
(7) Measure the sensitivity to identify the crucial state variables
(8) Measure the sensitivity to the elimination of alternatives

In this project the first step was to define and bound the decision problem. In this particular case, the various abatement technologies (i.e., whether to use clean fuels as an alternative, etc.), were identified. The basic decision problem was thus how to fund various abatement or clean fuel technologies in order to minimize SO_2 levels at minimum cost to industry.

The next step was to identify outcomes that would be sufficient to describe the results of various alternatives. This was total annual cost and mills/kwh. In relating outcomes to the alternatives we defined the factors that were relevant to the decision. These factors were separated into decision variables (factors that can be controlled) and state variables (factors

that cannot be controlled). The decision variables had been identified by Kellogg as consisting of various process parameters, coefficients, flow rates for certain processes, energy requirements for certain processes for a certain size plant, etc.

The state variables, which cannot be controlled but for which a distribution of values can be predicted, were energy demand, industrial growth, utility growth, price of coal, cost of labor, etc.

1. Description of Alternatives

The Kellogg Company has prepared process and cost models for the following specific processes for four SO_x control technology groups:[1]

(1) Throwaway flue gas cleaning process: the wet limestone scrubbing process
(2) Regenerable flue gas cleaning process: the Wellman-Lord process
(3) High-Btu gasification process: production of pipeline quality synthetic natural gas by Lurgi coal gasification process
(4) Chemical coal cleaning process: the solvent-refined coal process

2. Description of Process and Cost Models

Kellogg's process and cost models were prepared by relating the key process variables with equipment sizes, utility consumption (cooling water, process

water, power, natural gas, and steam), raw material requirements, and by-product, if any. For example, the Lurgi coal gasification process (for pipeline-quality synthetic natural gas) contains two key independent variables: 1) the substitute natural gas production rate, and 2) the oxygen content of the dry, ash-free coal. Two minor independent variables are the plant stream factor and the sulfur content of the coal. The process and cost model for the Lurgi high Btu process were based upon these process variables.

The Kellogg cost models estimate the total capital investment and the annual operating costs. The total capital investment is a function of:

(1) key process variables
(2) the retrofit difficulty factor
(3) the location

The relationship between factors included in the total capital investment and the total operating costs are shown in Figures 2 and 3, respectively.

In Kellogg's cost model, fixed costs (Figure 3) are based on 18.25% of the total capital investment (TCI) for 15 years plant life and 16.75% of TCI for 20 years plant life. The TCI includes cost of site, working capital, startup costs, and interest on construction capital (Figure 2). The fixed costs are not a function of these expenses. Therefore, the accuracy of the annual

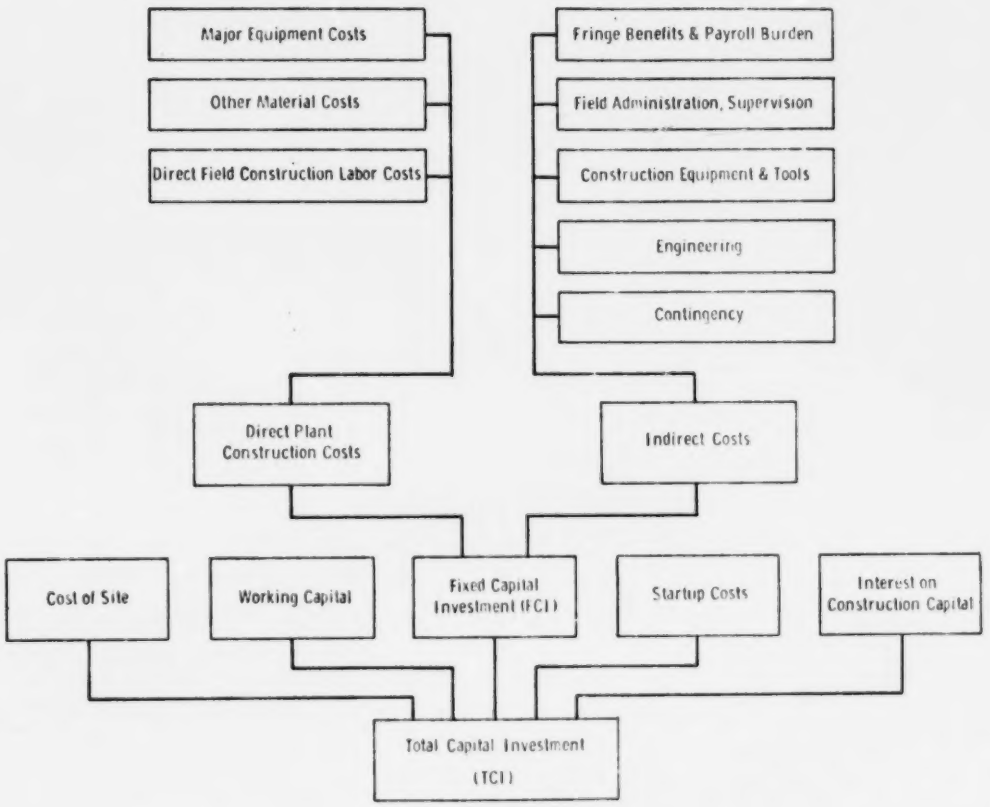

Figure 2. Relationship between factors included in the total capital investment

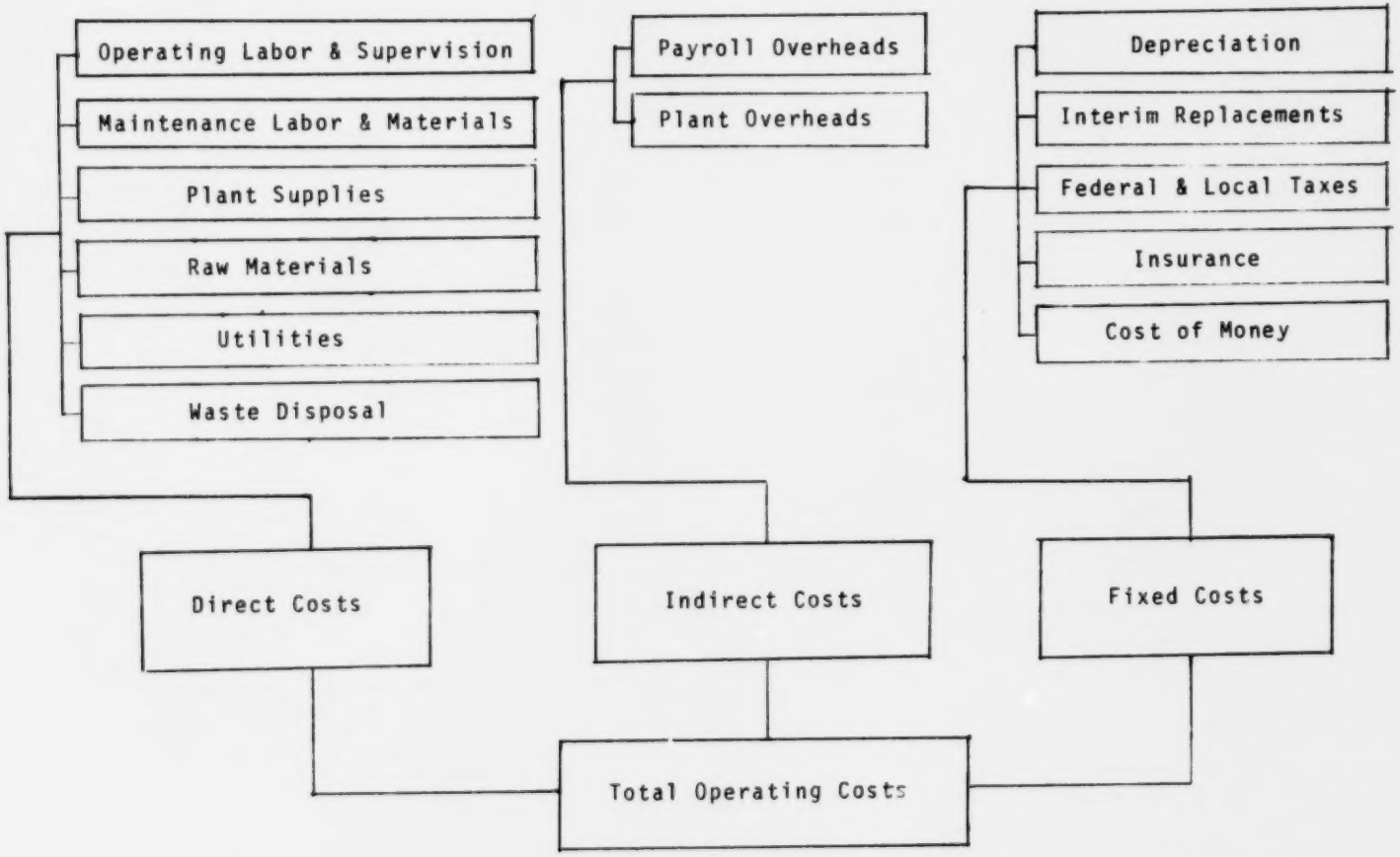

Figure 3. Relationships between factors included in the total operating costs

operating cost estimate would increase if the fixed costs were based on a certain percentage of the fixed capital investment (FCI) rather than the TCI.

The MRC cost models identify the most sensitive parameters of cost, including process variables and non-process variables. Process variables such as plant size, flue gas volume, etc., are derived from the process model. Non-process variables consist of items such as capital charge rate, load factor, utility costs, credits for by-products, etc. The most sensitive parameters were identified by varying process and non-process variables over a range of values. The effect of each parameter on both plant investment and operating costs was then determined.

SECTION VI

SIMULATION ANALYSIS

As was discussed in the introduction, a simulation approach was used, since the inputs were not normally distributed and since we are dealing with uncertainty. As an example, the distribution of sizes for coal-fired electric utilities is log-normally distributed. A sample log-normal distribution is shown in Figure 4. Figure 5 shows what would be an example of a normal distribution. These are true frequency distributions. The frequency distribution cannot be used for sampling purposes. We used instead the cumulative density function (or distribution), which is an integral of a function such as shown in Figure 6. The cumulative density functions of both the normal and the log-normal distributions are shown in Figures 6 and 7, respectively.

An example of the way a cumulative distribution is used is illustrated in Figure 8. The dashed line going from the 0.60 point on the ordinate to the curve selects the value for that particular level and indicates that 60% of the values for x will be less than 3.5.

During a simulation, several distributions such as that shown in Figure 8 were sampled and a range of values was computed. To perform this sampling, a digital computer which generates uniform random numbers between

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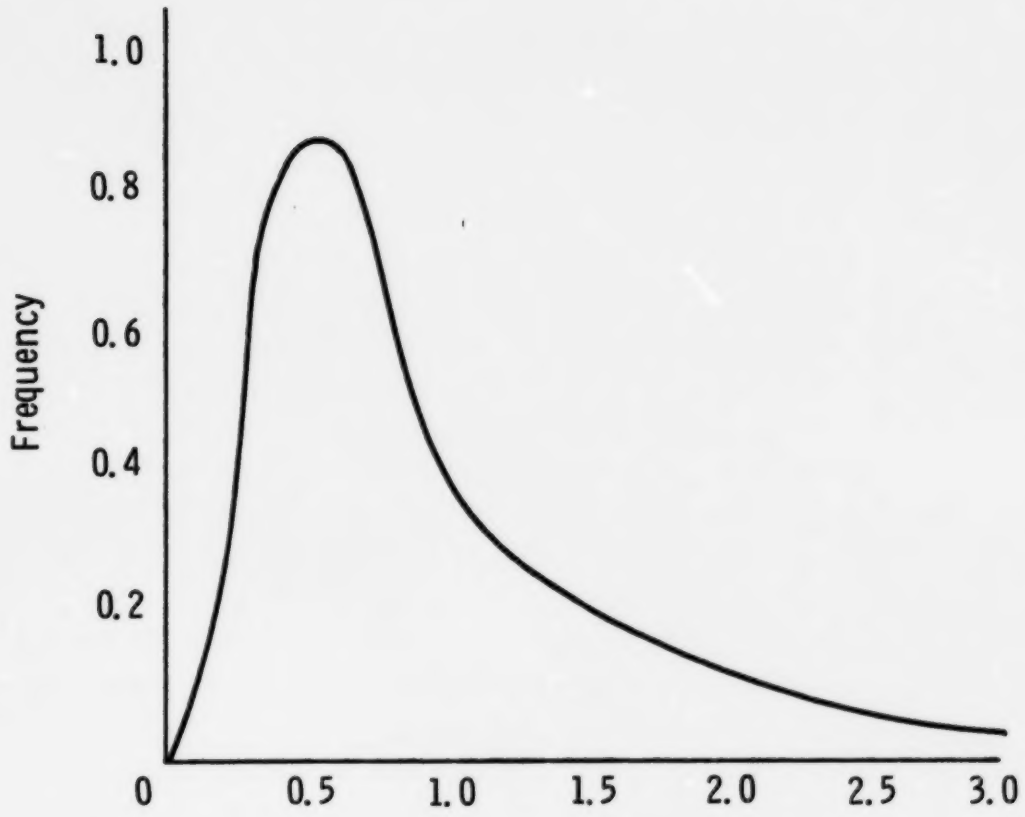


Figure 4. Sample log-normal probability distribution

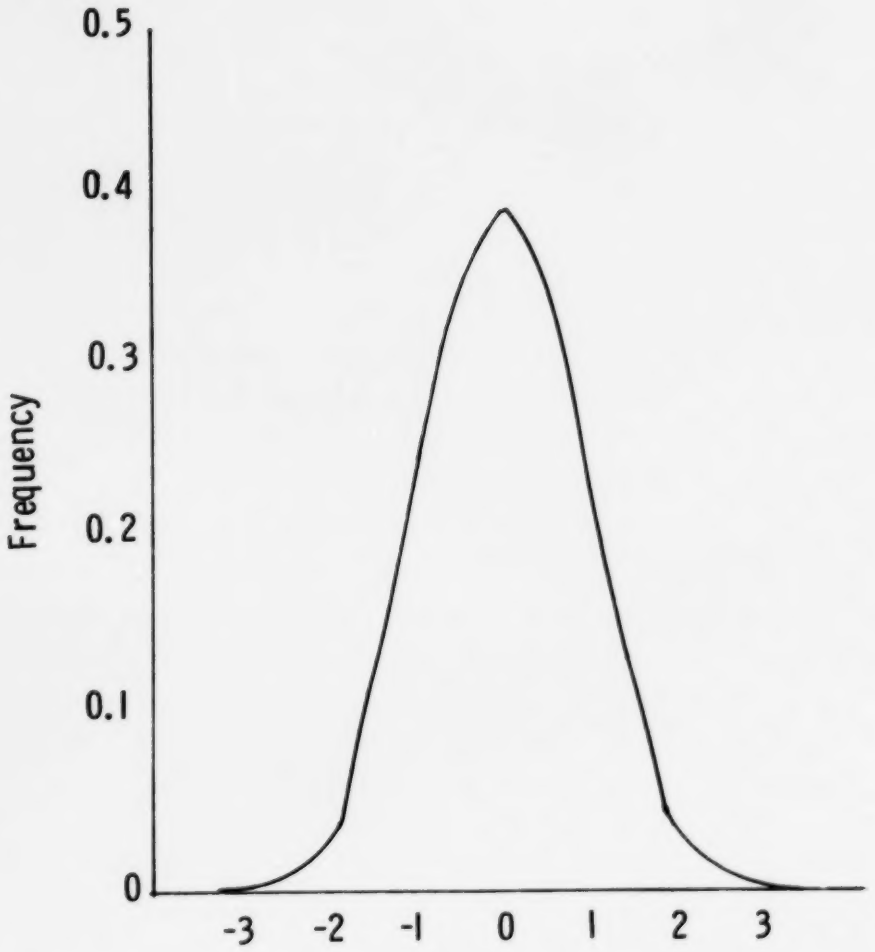


Figure 5. Sample normal probability distribution
(Units in standard deviations from mean)

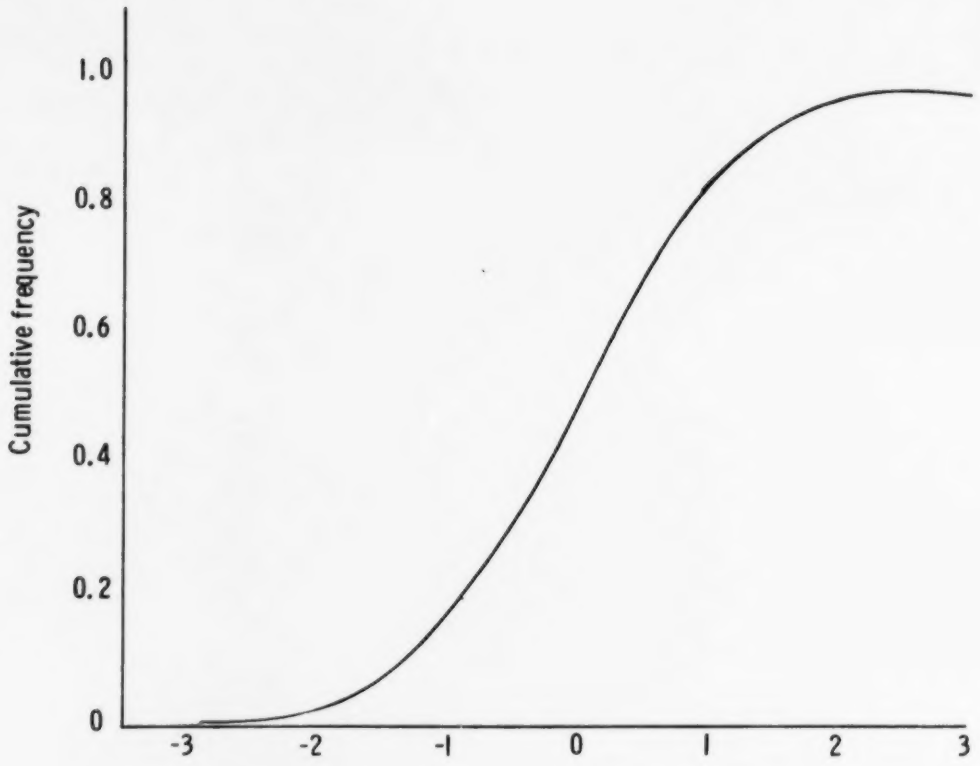


Figure 6. Normal cumulative density distribution

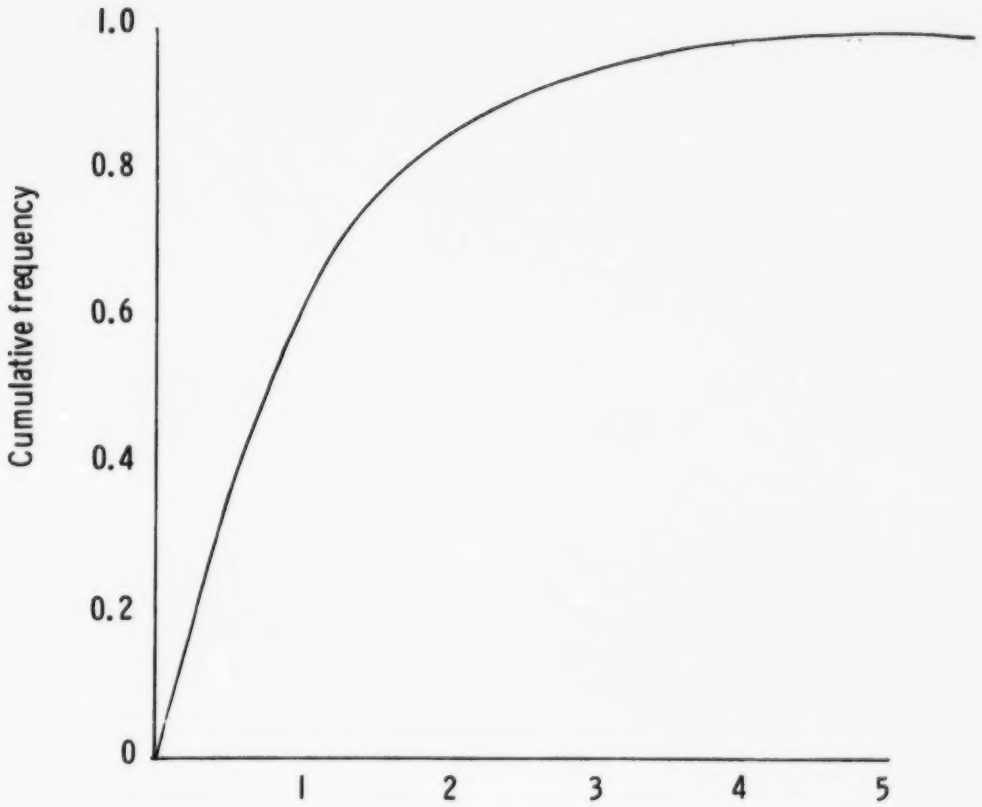


Figure 7. Log-normal cumulative density distribution

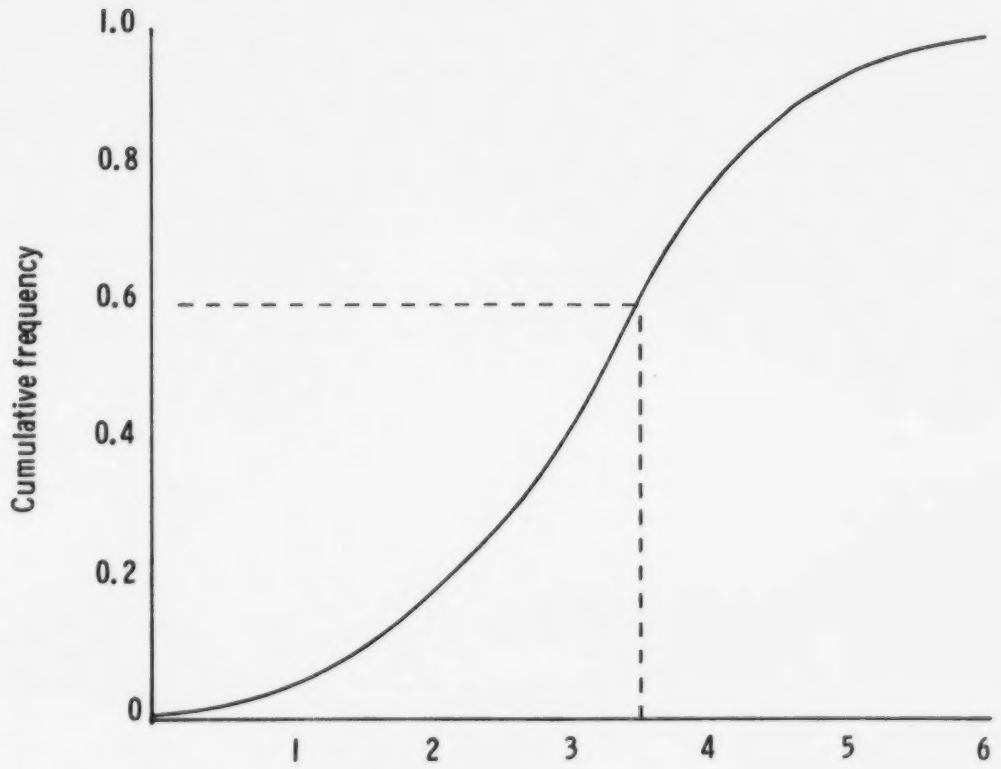


Figure 8. Example of using cumulative density function

0 and 1 was used. Essentially, the process is the same as selecting a random number, finding its intersection with the cumulative distribution curve, and determining a value for the variable of interest. Using that value throughout the calculation, a result is obtained and saved. The process is repeated several thousand times, and then the calculated values are used to generate a frequency histogram such as that shown in Figure 9.

If the input distributions are normally distributed, then one can use statistical mathematics to calculate the resulting distributions. In the present case, the distributions were not normal. We therefore used another distribution that had an analytical solution to an integral as defined by the following equation:

$$F(x) = \int_{o}^{x} f(z)\, dz \qquad (1)$$

The Weibull distribution[4] can approximate the log-normal distribution, the normal distribution, the Bernoulli distribution, and many others merely by a change in parameters. There are also analytical functions that describe both the probability density function and the cmulative density function. The following equations describe the Weibull cumulative density function, the probability density function, and a way of calculating independent variables from uniform random numbers (R_u), respectively:

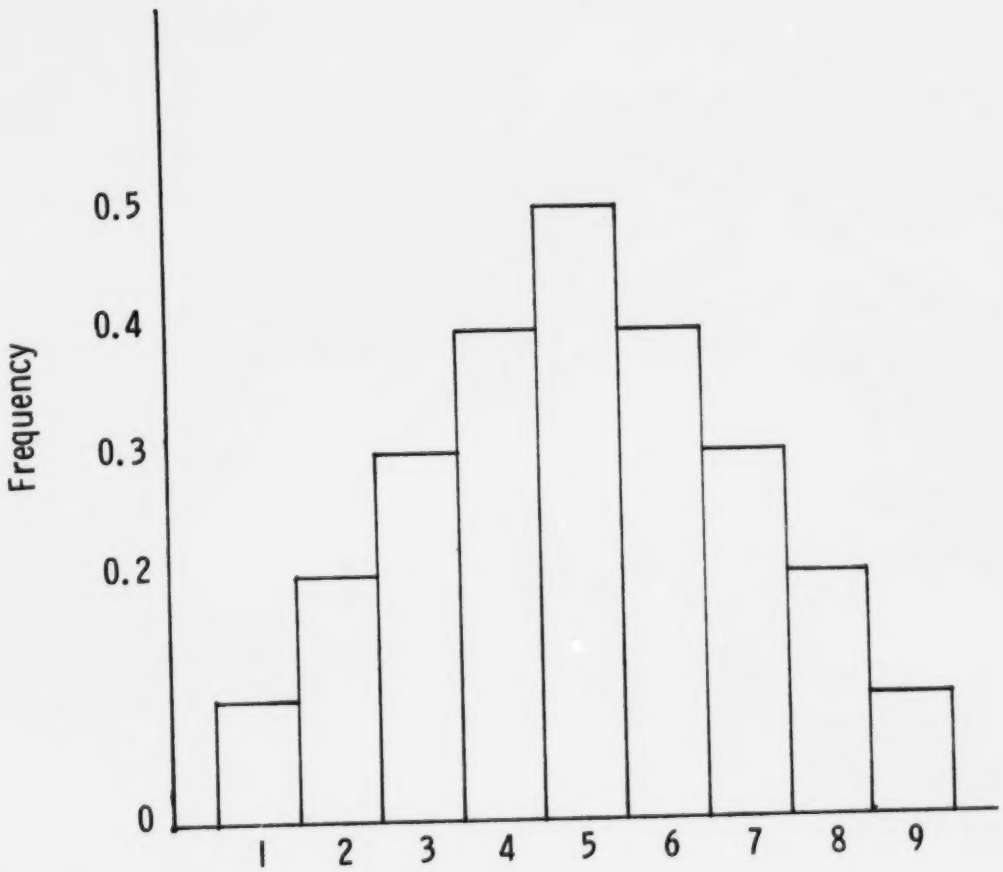


Figure 9. Sample frequency histogram

$$F(x) = 1 - \exp(-ax^b) \tag{2}$$

differentiating,

$$f(x) = abx^{b-1} \exp(-ax^b) \tag{3}$$

$$x = \left[\frac{-\ln(1.0 - R_u)}{a}\right]^{1/b} \tag{4}$$

$$F(x) = R_u$$

where a, b, and $x > 0$.

The analysis then proceeds as follows. Let the distribution be as shown in Figure 8. We define it as the Weibull cumulative density function and calculate the parameters a and b. Using equation 2, we transpose, invert and take double natural logarithms to obtain:

$$\ln \ln \left[\frac{1}{1 - F(x)}\right] = b \ln x + \ln a \tag{5}$$

Having transformed the cumulative density function into a linearized expression, we can now plot it in the slope-intercept form. We perform a least squares analysis on the computer and obtain the parameters a and b from the slope and the intercept:

$$\text{define} \quad \overline{Y} = \ln \ln \left[\frac{1}{1 - F(x)}\right] \tag{6}$$

$$\overline{X} = \ln x \tag{7}$$

$$K = \ln a \tag{8}$$

The least squares analysis is performed on the following:

$$\overline{Y} = b\overline{X} + K \tag{9}$$

One of the advantages of a Weibull function is the flexibility of its expression. This is true because b, a shpae parameter, really makes the function a family of curves. When b equals 1, the probability density function is the familiar log-normal distribution. The Rayleigh distribution, which deals with the distribution of errors in a two-dimensional grid, is obtained when b is equal to 2. When b equals 3.25, the Weibull distribution closely approximates the normal distribution. This is shown in Figure 10. Having obtained values for a and b, we now sample from a distribution by using equation 4. Since the Weibull function is continuous, it will have values for all ranges of x from zero to infinity, and since the random number generator could conceivably select a random number such as 0.99999, we would get an extremely large magnitude for a value of x. Therefore, in order to restrict the sampling range, we restrict the range of the uniform random number generator and calculate a transformed number R_t by performing the following:

$$R_t - c_1 R_u + c_2 \tag{10}$$

Thus, if we want a lower random number R_ℓ and a high limit number R_h, we would use the uniformly generated numbers 0.0 and 1.0 and solve the following simultaneous equations for c_1 and c_2:

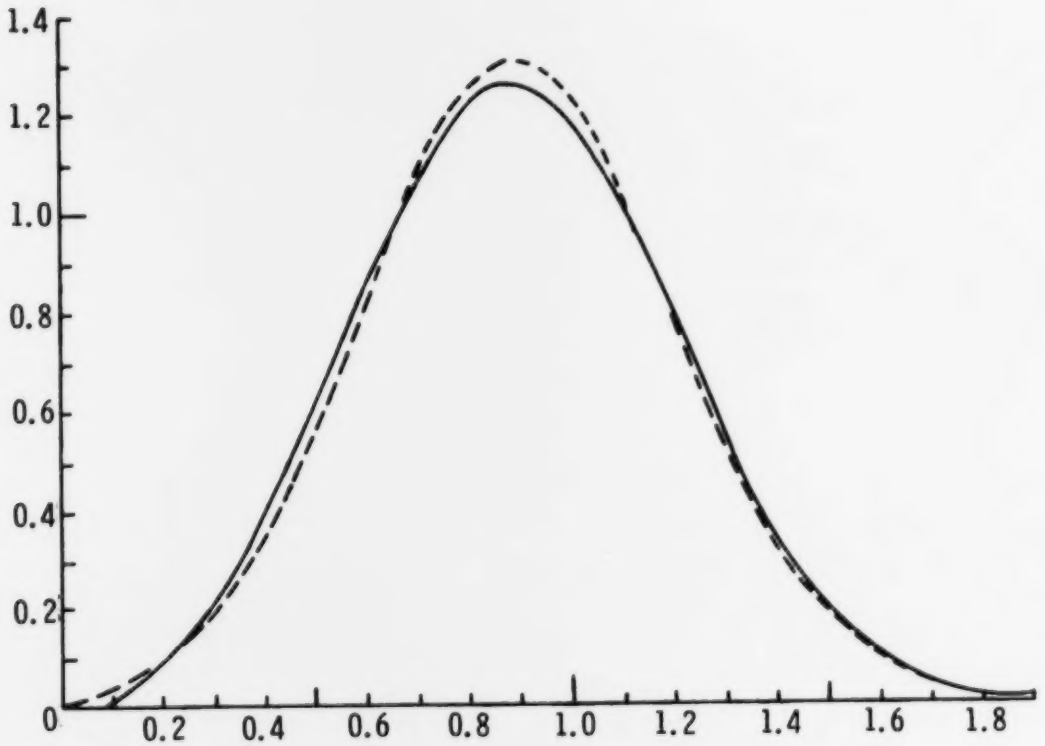


Figure 10. A comparison of the normal and Weibull distributions

$$R_\ell = c_1 (0.0) + c_2 \qquad (11)$$

$$R_h = c_1 (1.0) + c_2 \qquad (12)$$

Thus, if we want to limit the sampling to be between 0.99 and 0.01, we would make the following transformation on the random number generator:

$$0.01 = c_1 (0.0) + c_2 \qquad (13)$$

$$0.99 = c_1 (1.0) + c_2 \qquad (14)$$

then $c_1 = 0.98$

$c_2 = 0.01$

Therefore,

$$R_t = 0.98 R_u + 0.01 \qquad (15)$$

This type of transformation can be performed on any of the input distributions.

SECTION VII

IMPACT ASSESSMENT METHODOLOGY

A. STATE VARIABLE ANALYSIS

Defined generically, state variables are those that can affect the success or failure of a decision-maker's operations but which are essentially beyond his ability to control. For instance, during the last year major international airlines have experienced severe financial problems because of large, arbitrary increases in the price of aviation fuel which is an important item of their costs but over which they have no control.

A manager of an electric power plant or an industrial plant, such as a smelter, also has to cope with state variables when he decides which type of technical process he should install to reduce the volume of SO_x emissions that fuel combustion in his plant generates. Table 1 lists some of these state variables.

It would be costly, time-consuming, and methodologically difficult to incorporate a large number of state variables into an analytical model that a Government R&D agency,

like EPA CSL, might employ. Fortunately, screening criteria can be employed to reduce a large list, such as that provided in Table 1, to manageable proportions. Several of these criteria are defined below.

Defineability and Measurability

Unless a clear consensus can be reached relative to the meaning of a variable and a quantitative method developed to measure it, it is very difficult to handle that type variable in a formal analytical model. For instance, political strategies of both the oil importing and exporting nations are relevant state variables, but such strategies are at this point not susceptible to systematic analysis.

Data Availability

Unless a reasonable quantity of historical data is available, there is no basis from which to project the future status of a state variable. For instance, potential equipment shortages, such as new stack scrubbers now under development, could be a relevant state variable that would affect the decisions of companies relative to the choice of SO_x control technologies. However, there is very little statistical information from which to project such potential shortages.

Table 1. ILLUSTRATIVE STATE VARIABLES APPLYING TO THE CHOICE OF SO_x CONTROL TECHNOLOGIES

Market Costs of Production Factors

Labor
Land
Construction
Equipment
Materials and supplies
Transmission and distribution
Financing (interest rates)
Waste material disposal
etc.

Competitive Fuel Relationships

Coal, Oil, Gas, Hydro, Nuclear, etc. — Supply & Price

Consumer Elements

Per capita requirements for energy
Choice of fuel for heating, etc.
etc.

Government Regulations

Effecting supply
- Strip-mining controls
- Off-shore oil policy
- Licensing (e.g., AEC, pipe lines, transmission lines)
- Other public land leasing
- etc.

Effecting costs
- Strip-mining land restoration requirements
- Oil depletion allowances, taxes, etc.
- etc.

Table 1 (Cont.) ILLUSTRATIVE STATE VARIABLES APPLYING TO THE CHOICE OF SO_x CONTROL TECHNOLOGIES

Effecting both supply and costs
- Mine safety & health regulations
- etc.

Effecting fuel usage
- Clean-air regulations governing use of polluting fuels
- etc.

Effecting consumer demand
- Various rationing measures
- etc.

Effecting prices and rates
- ICC rates for transportation
- Natural gas price controls

International Considerations

Political Policies: Fuel Exporting Nations (OPEC)
Consumption Patterns: Fuel Importing Nations (Japan, Common Market, etc.)
etc.

Logistical Constraints

Shortages of labor (e.g., coal miners)
Shortages of transportation (e.g., pipe lines)
Shortages of equipment (e.g., stack scrubbers)
Shortages of desirable fuels (low sulfur, coal, natural gas, etc.)
Other resource shortages (e.g., water)
etc.

Technological Parameters

Amount of R&D funding
Supply of scientists and research facilities (time lags)
etc.

A Substantial Item

If an item of cost or credit is relatively small, even if it is measurable and affects different SO_x technologies to a different degree, it would not be worthwhile to include it in the analysis. The revenues that certain processes might make possible through the sale of some byproducts is an example.

Taking all of these factors into consideration, and using the results of the sensitivity analyses, we have selected the price of coal as an illustration of state variable analysis. Besides the sensitivity analyses, we have consulted approximately a dozen different government and private sources in reaching the conclusions that follow:

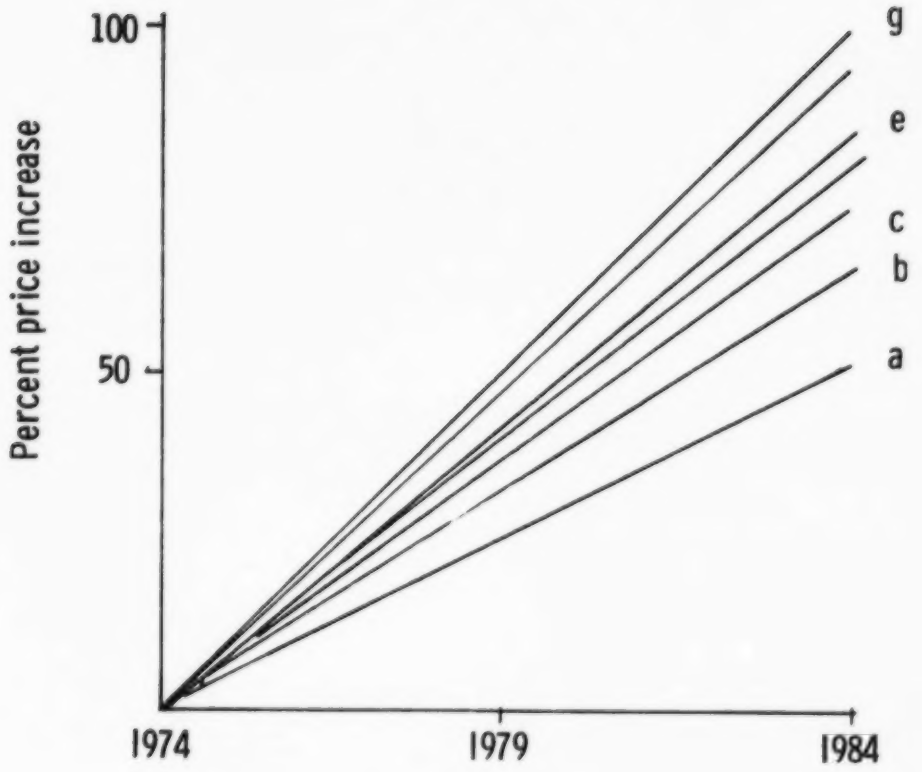
For two reasons, it appears that the trends in the price of coal will work toward the competitive advantage of the Solvent Refined Coal (SRC) process as opposed to the Lurgi-Synthetic Natural Gas (SNG) process. The average price for coal is expected to double in the next decade whereas the general cost of living and most industrial prices are expected to increase by only 50%. These two factors mean that a process, such as SNG, which is more sensitive to the price of coal would be at a competitive disadvantage compared to another process, such as SRC, which is less sensitive to the price of coal.

It is very difficult to project rationally what level the price of coal will actually reach a decade from now. In the last year, coal sold under contract doubled in price. Non-contract coal (spot purchases) increased by as much as 1,000 percent to $120 per ton in some instances.

Most observers, perhaps as an article of faith and hope, anticipate that future percentage increases in the price of coal will be much less annually over the next decade than they were in the last year. Our own projection that the price of coal will double in the next decade (see Figure 11) is based more on certain fundamental long-term trends than in terms of last year's experience. First, for about five years the price of coal increased much more sharply than did the average of other prices. Second, there is evidence that future increases in the price of coal will considerably exceed increases in the general price level.

The projected 100% increase in the price of coal in the next decade will result from the combined action of many factors:

a. Fifty percent of this increase will result from a general inflation in all prices, domestic and foreign. This continued inflation means that all of the costs - wages, equipment, materials, etc. - involved in producing a ton of coal will, on the average, increase at this 50% rate. This projected annual average increase for the next decade of 5% roughly equals the average annual increase in the 1964-1973 period as shown in Figure 12.



Code:

a - general inflation
b - market competition for all fuels
c - shortages of mining labor
d - safety and health regulations
e - strip mining compliance
f - additional transportation costs
g - declining labor productivity

Figure 11. The price of coal in 1984: A projected index with explanatory factors
1974 = 100

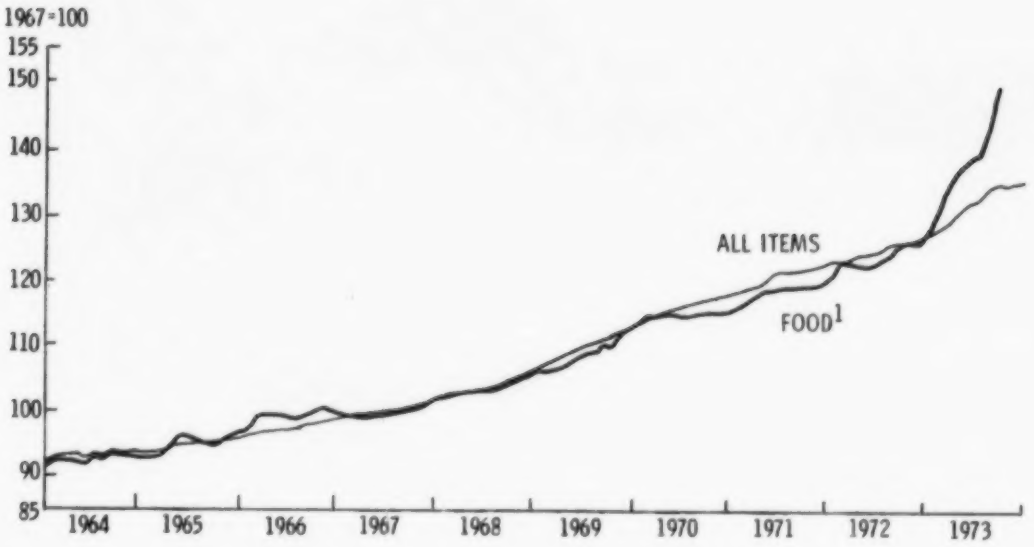


Figure 12. Consumer price index (all items)[5]

b. Fifteen percent of this increase will be due to market place competition that forces up the prices of all fuels at a faster rate than the increase in prices generally. this relative increase in fuel prices will be due partly to a growing domestic and world demand for energy, coupled with a tight supply. The nation's drive to satisfy a larger percentage of its total energy needs from domestic sources will contribute to the tightness in energy supply.

This greater-than-average increase in the prices of fuel, taken as a group, as compared to prices generally, is reflected by the data reported in Table 2.

Table 2. INCREASES IN THE PRICE OF FUELS* COMPARED TO GENERAL PRICE INCREASES[6]

1967 = 100

	Annual Average 1973	September 1974
Fuels	134.3	225.0
All prices	134.7	167.2

*Includes coal, coke, gas fuels, electric power, crude petroleum, refined petroleum products

c. Ten percent of this increase will be due to a shortage of coal miners that will push their hourly rate up faster than the average of wages in other industries. This labor shortage will be due partly to the fact that older miners will be retiring at an earlier age, and their sons will be migrating to the cities to seek other types of more attractive work rather than working in the mines. The declining labor force in all types of mining has been a very long run trend extending over a period of at least 35 years, as the data in Table 3 reveal.

Table 3. EMPLOYMENT IN MINING[7]

Year	Employment
1947	955,000
1952	898,000
1957	828,000
1962	650,000
1967	613,000
1972	607,000

This declining labor force in mining, especially coal mining, is at variance with trends in other sectors of the economy as indicated in Table 4. These data show that whereas in other sectors of the economy employment has increased by an average annual rate of 2.7%, in coal mining it has decreased 4.4% annually. Even with all of the pressures to increase coal production in the balance of this decade, it is anticipated that for the twelve-year period 1968-80, coal mining employment will increase at less than one-half the rate of the increase in employment generally. Finally, it is estimated that after 1980 there will be no increase at all in coal mining employment.

Table 4. EMPLOYMENT IN COAL MINING COMPARED TO ALL TYPES OF NON-AGRICULTURAL EMPLOYMENT[8] (average annual percentage change)

	Average Annual Percent Change		
	1959-68	1968-80	1980-85
Total non-agricultural employment	2.7	2.4	1.4
Mining	-4.4	1.1	0.0

d. Six percent of the increase will be due to new mine safety and health regulations, and a stricter enforcement of existing regulations. The estimated impact of safety and health regulations is primarily an assessment of the effect of the Federal Coal Mine Health and Safety Act that became effective in April 1970. This Act, which is designed primarily to make the physical mine safe, has been in effect too short a time and the evidence accumulated to date is insufficiently complete, to permit conclusive judgements. However, some observers have contended that the impact of this Act, has been to reduce production by 15 to 25% and to increase the per ton cost of coal 20 to 30%.[9]

e. Six percent of the increase will be due to the costs associated with compliance with new stricter strip-mining regulations. Here again, judgements must be formed on very incomplete information. As this report is being written, (December 1974), the U.S. Congress is involved in a heated debate relative

to passing new strip-mining legislation. Whether or not such legislation passes at this session of the Congress, stricter strip-mining legislation is highly likely. For one thing, the more liberally-oriented Congress that took office early in 1975 might pass such legislation. Perhaps more important is the fact that individual states, such as Pennsylvania, have already passed much stricter strip-mining laws than the pending Federal legislation. The cost of reclaiming land that has been strip-mined varies considerably depending upon such factors as the terrain of the land and the depth of the coal deposit under the strip-mined surface. One set of estimates that generalizes on these costs is shown in Table 5.

Table 5. TYPICAL COSTS OF RECLAIMING LAND THAT HAS BEEN STRIP-MINED[10]

Mining Area	Dollars per Acre	Dollars per Ton	Cents per kWh
Eastern States	$3,000-5,000	$1.00-3.00	0.3-0.10
Western States	$1,000-4,000	$0.20-2.00	0.001-0.01

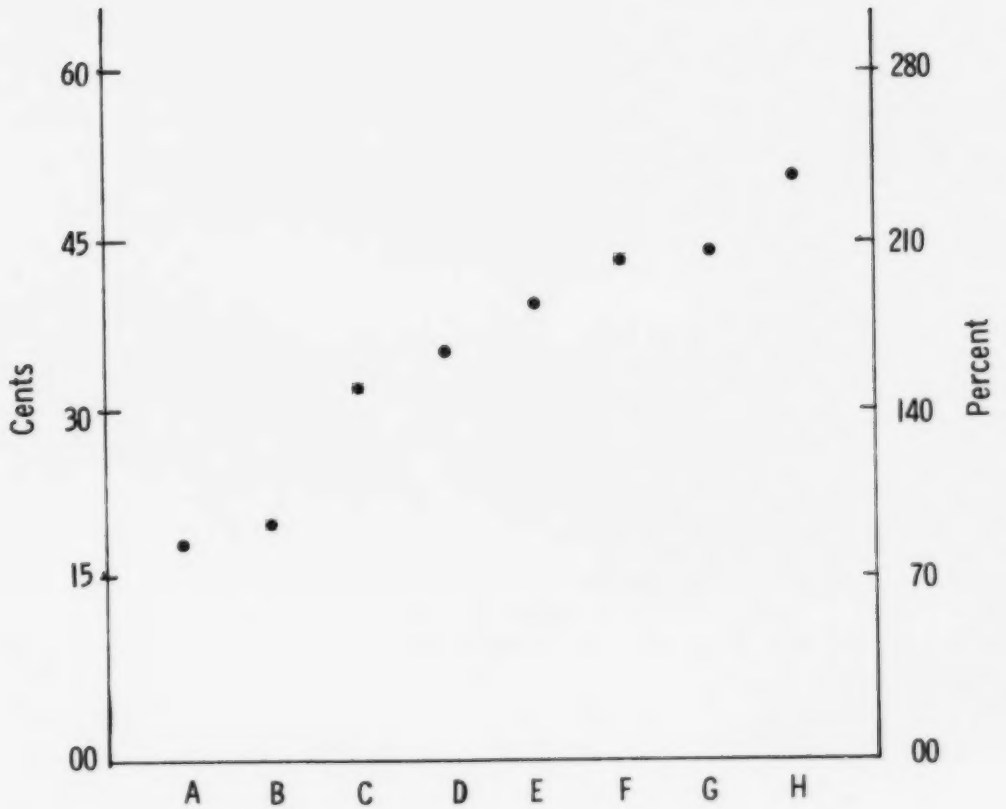
f. Eight percent of the increase will be due to the spiraling costs of transporting coal to market. Except for a slight dip in 1972, the per-ton costs of transporting coal to market have steadily increased since 1968, as shown in Table 6. Although published data were not available to us at the time this report was being written, it is our understanding that the rise in transportation costs has

continued in the two years since the last date shown in Table 6. Of course, the farther away that users are from the coal mines, the greater will they feel the impact of increases in the costs of transporting coal to market. The difference in the transportation costs is one factor that explains why it costs so much more for electric power plants in some regions of the country to use coal as a fuel than in others. For instance, the costs of steam electric power plants using coal in New England are more than twice as much as in the west south-central states. Other regions fall between these two extremes as shown in Figure 13.

Table 6. AVERAGE PER TON COSTS OF TRANSPORTING BITUMINOUS COAL TO MARKET[11]

Year	Costs per Ton	Price Index
1968	$ 3.02	100.00
1969	3.12	103.31
1970	3.43	113.58
1971	3.72	123.18
1972	3.68	121.85

g. Five percent of the increase will be due to declining labor productivity in the coal mines. There is considerable evidence to substantiate this productivity problem. For instance, a Federal report shows that coal mining was the only one of approximately 50 manufacturing, mining, transportation, and other industry sectors that registered



Code:	Cents	%
A - West, South Central States	21.0	100
B - Mountain States	22.7	108
C - East, South Central States	32.5	154
D - West, North Central States	34.0	162
E - East, North Central States	38.9	178
F - Middle Atlantic States	42.1	200
G - South Atlantic States	42.6	203
H - New England States	49.7	237

Figure 13. Regional differences in the costs of coal for steam electric power plants (Unit of measure: "As Burned" cents per million Btu, 1972)

a decline in output per manhour in the 1968-1973 period.[13] Figure 14, based on data from the U.S. Bureau of Mines, shows the extent of this decline.

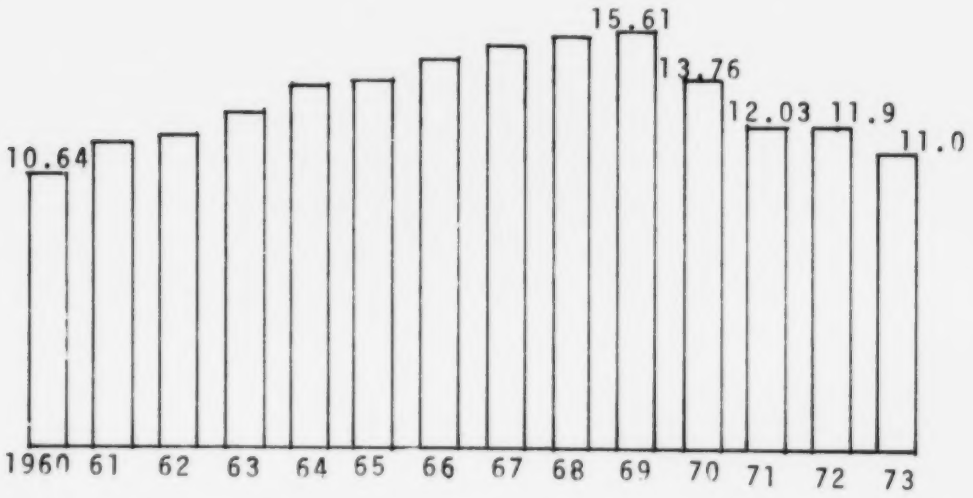


Figure 14. Underground mining productivity[14]

Taking all mining as a class, government analysts have projected that over the next decade the improvement in productivity will be much less than in other sectors of the private economy. These data are shown in Table 7.

Table 7. PROJECTED INCREASES IN LABOR PRODUCTIVITY[15]
(Annual Average Percentage Increases)

	1972-80	1980-85
Total private economy	3.2	2.8
Mining	0.9	0.8

Several factors account for the fact that productivity will continue to be a problem in the mining industry. The shortage of miners will bring into the labor force marginal, less efficient workers who would not be employed if it were not for the labor shortage. A contributing factor will be the restlessness and low morale of men who work in the mines. Although a decade from now mining wages will compare favorably with many other industries, and working conditions in the mines will be much improved over those today, still, the amenities and fringe benefits provided to miners will be fewer than those provided to other trades, occupations, and professions.

B. DISCUSSION

The primary purpose of this report has been to illustrate how one would approach a state variable analysis and present the findings in a relatively simple fashion. The specific projection that the price of coal will double in the next decade is based on several optimistic assumptions:

a. The 50% increase in general inflation over a period of a decade, assumed above, is highly optimistic by recent standards. In other words, we have assumed that general prices will increase by an average of only 4% per year in the next decade as compared to the 12% experienced in the last year.

b. We have also assumed that a persistent energy shortage can be kept from becoming a major crisis. This optimism is based on an expectation that the nation will be able to bring many more nuclear plants into operation and will be able to tap the oil of the Atlantic coast, the Alaskan slopes, and that recently discovered in Mexico.

c. We have also assumed that the petroleum-using countries and the OPEC nations will be able to come to terms to maintain a high supply of mid-east petroleum at relatively stable prices.

If one or more of these optimistic assumptions fail to materialize, the rise in general prices will certainly be much higher and the rise in coal prices proportionally larger than our projections indicate.

The foregoing relatively optimistic scenario is, of course, only one of many possible scenarios. One alternative would be to assume that the nightmarish inflation that has plagued the United States and other nations in the last year will become the new "wave of the future." A comprehensive, probabilistic analytical model would generate not only one scenario for the price of coal, but a whole series of them based on different assumptions relative to the values of major parameters.

Finally, a comprehensive, probabilistic, analytical model would incorporate an analysis of many of the other state variables listed in Table 1. One other such variable might be the price of construction labor in various parts

of the country. For instance, over the last five years construction labor wage rates have increased considerably more on the east coast than in central or western states. This is shown in Table 8. Various factors explain this fact. One of these has been the relatively heavy industrialization of the south. A related one has been the building boom in Florida and other states that has accompanied this industrialization plus the migration of retired people to that area. Finally, the greater unionization of labor in southern states has tended to reduce historical differences in construction industry wage rates. In any event, projected regional differences in percentage changes in construction labor costs could very well influence the choice that plant managers will make in the coming decade as to which of the various SO_x control technologies they would decide to adopt.

Table 8. AN INDEX MEASURING REGIONAL DIFFERENCES IN THE INCREASE IN UNION WAGE RATES IN THE CONSTRUCTION FIELD* IN THE 1969-74 PERIOD

Region	Index
Western States	100
South Central States	115
East, North Central States	116
West, North Central States	119
North Eastern States	128
South Eastern States	131

*This index is a weighted average using sheet metal workers, electricians, and laborers. Basic data were taken from: CMA News, Contractors Mutual Association, Washington, D.C., March 1, 1974.

SECTION VIII

EFFORTS REQUIRED FOR A REALISTIC ANALYSIS

One basic assumption in this analysis is that the clean fuel facilities will be located at or near the coal mine mouth. If this is an unwarranted assumption, there is nothing in the method that prevents us from including a transportation cost distribution to these facilities. However, viewing this aspect realistically, we feel that quite the reverse might well be true, i.e., not only would the clean fuel facilities be located at the mine mouth and thus not incur any transportation cost, but also these facilities might well be owned or jointly owned by the mining company supplying the coal, thereby resulting in a lower mine mouth cost of coal to this facility. Since the cost of coal is an important variable, clean fuel facilities provide coal with different heat contents and thus resulting transportation costs, this aspect warrants additional attention.

On the other hand, this analysis used a somewhat arbitrary distribution for transportation distances for coal to the using utilities. Again, since the same distance distributions were used for clean or dirty coal, the only effect this has is that the utility vs. industrial boiler cost comparisons may not be valid. The relative cost comparison of the four alternatives for utilities or industrial boilers is valid with

respect to transportation distance. Naturally, the absolute value for mills/kWh is a function of many things and it was not the objective or scope of this work to arrive at absolute values of cost. We have raised questions about the validity of the clean fuel cost models. These questions and objections can be treated with cur approach. Any portion of the process or cost models that is deterministic can be treated probabilistically to take into account undemonstrated process reliability. This in turn can be reflected in uncertainty of equipment size, reaction times, reactant or catalyst amounts required, etc. Process complexity and thus unforeseen increased manpower requirements for any segment of the process can be treated with our methodology. Deterministically this is easy to follow; e.g., there are problems with filtration in the SRC process due to unforeseen scale-up agglomeration. If we know this, we simply triple the equipment costs to indicate that more equipment will be necessary to successfully accomplish that particular process step. Or, the number of workers required for that step can be increased, thus increasing both capital and operating costs. But since the process has not been demonstrated commercially and we do not know if the price of that piece of equipment should quadruple, triple, double, we now have a method of treating this uncertainty. This approach should have utility in allowing cost estimates to be made for undemonstrated processes.

Another very important aspect of a realistic analysis is the realistic projection of by-product disposal costs and by-product credits. Using SRC as an example, would the

increased availability of cresylic acid be an increased incentive for its utilization, thereby making its price relatively inelastic, or would its increased availability result in a glut on the market and contribute to a lower price? Again, the methodology we have developed would allow a treatment of this question.

We have data to show that the price of coal and its heating value are functionally related; the higher the heating value the higher the price. Percent sulfur and the price may be additionally related, however, we have no data to support this.

Transportation cost per unit distance was considered a constant, with the transportation distance being the statistical variable. We know that unit transportation cost is a variable as well, and a realistic analysis should take this into account.

In the flue gas scrubbing models we also have some unrealistic aspects. The Kellogg Company model for the Wellman/Allied process uses a separate train for each boiler. In actual practice, a common train would likely be used for all the boilers in a power plant. The percent sulfur removed is a constant for both scrubbing processes. In actual practice, it would be a function of the percent sulfur in the coal burned.

As a final comment, we feel that the unrecoverable release of sulfur into the atmosphere in any form will be highly undesirable due to the projected increasing worldwide demand for sulfuric acid. In the future, the economics of either

sulfur recoverable flue-gas desulfurization or clean fuel preparation are likely to become competitive with throwaway processes.

The methodology we have developed can be used for any number of alternatives. Realistic results will be obtained only from a well documented, thorough probabilistic analysis of process and cost uncertainties and all relevant input parameters affecting these alternatives. The objectives of this program were limited in the scope of results developed, but this program has shown the fundamentals of a way uncertainty can be treated in a quantitative manner. A realistic assessment of alternatives would require the modeling not only of the processes but also of the availability of construciton, transportation, capital, manpower and the seemingly intractable and intangible social, economic and political perceptions of utility viewed from highly subjective points of view. The methodology for doing these things is called Decision Analysis. We have taken a small subset from that science to show how it might be useful to the decision maker when he is operating under conditions that he faces every hour of every day, operating under conditions of uncertainty.

SECTION IX

EXAMPLE OF METHODOLOGY

Wellman-Allied Process - This process is based on a sodium sulfite/sodium bisulfite cycle to remove sulfur dioxide from the glue gas. The reactions that take place in the process are abbreviated as follows:

Absorption

$$SO_2 + SO_3^{=} + H_2O \rightarrow 2HSO_3^{-} \quad (13)$$

Regeneration

$$2Na^{+} + 2HSO_3^{-} \rightarrow Na_2SO_3\downarrow + SO_2\uparrow + H_2O \quad (14)$$

SO_2 Reduction

$$CH_4 + 2SO_2 \rightarrow CO_2 + 2H_2O + S_2 \quad (15a)$$

$$4CH_4 + 6SO_4 \rightarrow 4CO_2 + 4H_2O + 4H_2S + S_2 \quad (15b)$$

$$2H_2S + SO_2 \rightarrow 3/2\ S_2 + 2H_2O \quad (15c)$$

The process flow scheme, shown in Figure 15, can be divided into four main sections:

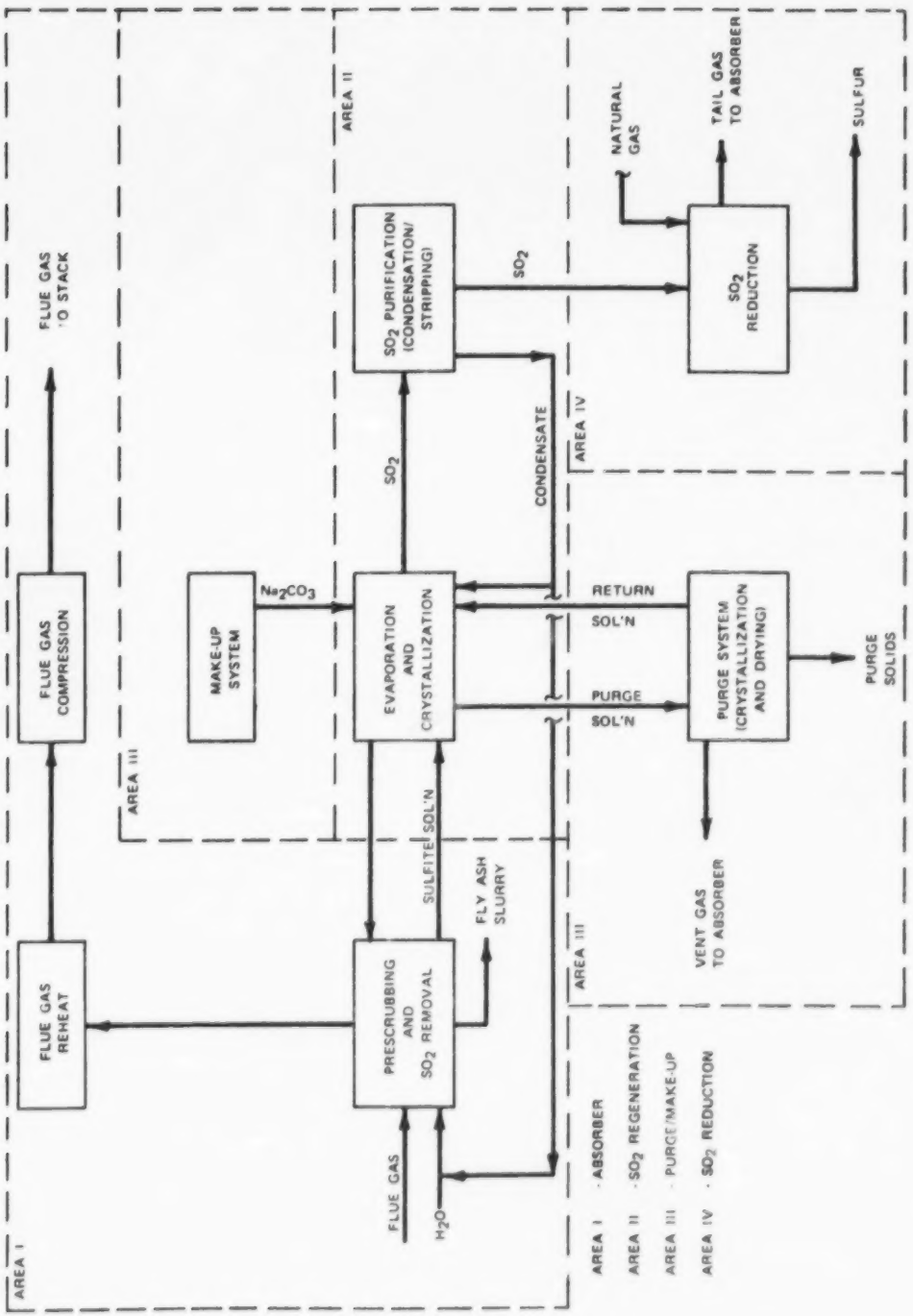


Figure 15. Wellman-Allied Process Flowsheet

(1) The absorber section, including gas reheat and discharge;
(2) The SO_2 regeneration section;
(3) The purge/make-up section; and
(4) The SO_2 reduction section.

The SO_2-rich gas is contacted countercurrently in the absorber by the sodium sulfite solution and exits from the absorber top stripped of SO_2. The solution leaving the bottom of the absorber is rich in bisulfite and is pumped to an evaporator/crystallizer in the regeneration section. Low pressure steam is used to heat the evaporator and drive off SO_2 and water vapor. The gas stream leaving the evaporator is partially condensed to remove the majority of the water vapor and is then discharged to the SO_2 reduction unit where natural gas is used to convert SO_2 to product sulfur.

To operate this scrubbing process, more coal feed to the boiler would be necessary to provide the electricity and steam required.

Cost Comparison Procedures

The major problem in comparing SO_x abatement methods of different generic types on a common cost basis is the finding of a common cost factor. The common cost factor used in this study is a summation of the annual costs of fuel, fuel handling, and flue gas desulfurization for each of the four methods as applied to utility power plants or industrial boilers.

Electric Utility Power Plants - In this industry, the following assumptions (based on M. W. Kellogg's work)[1] were made for each power plant to calculate the common cost factor:

- The number of boilers is 4 if the plant capacity is higher than 50 megawatts. This number becomes 3 is plant capacity is between 20 and 50 megawatts, and 2 if the plant capacity is between 10 and 20 megawatts. It is assumed that there is only one boiler in the plant if its capacity is less than 10 megawatts.

- When the number of boilers is 4, it is assumed that the distribution of the plant generation capacity among these boilers is 51.8%, 28.4%, 12.6%, and 7.2% of the plant capacity. The capacity distribution becomes 65%, 26%, and 9% of the plant capacity when the number of boilers is 3. This distribution becomes 75% and 25% when the number of boilers is 2.

- If the load factor for the first boiler is unity, the load factor for the second boiler is 0.75. The fraction is 0.55 for the third boiler, and 0.1 for the smallest one.

- All the sulfur content in the coal feed to the boiler becomes SO_2 in the flue gas.

- Each power plant has a load factor of 0.5.

Wellman-Allied Process - A general procedure is shown in Figure 16. The calculations can be grouped into three areas. Area I contains the calculations associated with the operation of the power plant itself. No cost is involved in

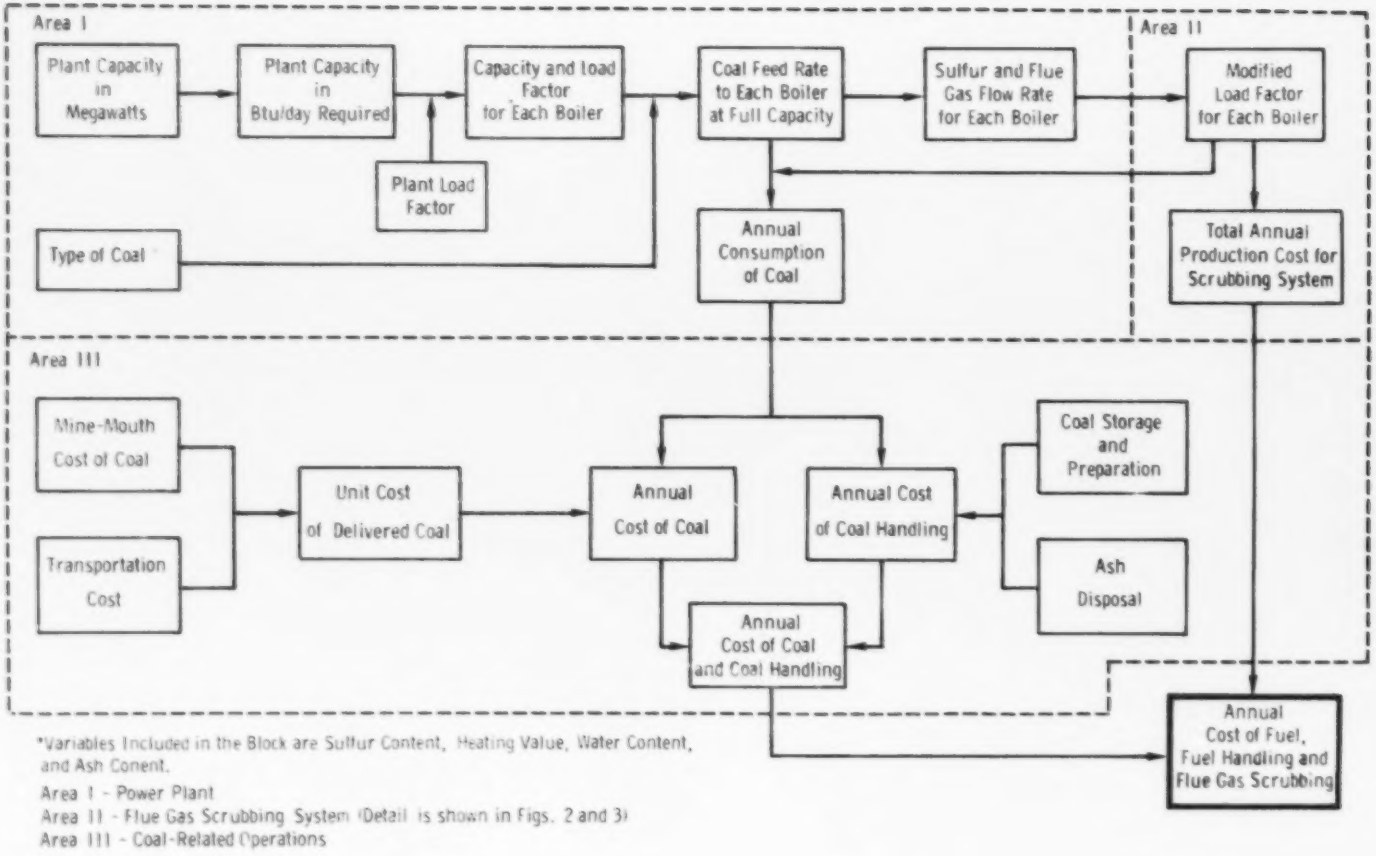

Area I
Plant Capacity in Megawatts
Plant Capacity in Btu/day Required
Capacity and Load Factor for Each Boiler
Plant Load Factor
Coal Feed Rate to Each Boiler at Full Capacity
Sulfur and Flue Gas Flow Rate for Each Boiler
Area II
Modified Load Factor for Each Boiler
Type of Coal
Annual Consumption of Coal
Total Annual Production Cost for Scrubbing System
Area III
Mine-Mouth Cost of Coal
Transportation Cost
Unit Cost of Delivered Coal
Annual Cost of Coal
Annual Cost of Coal Handling
Coal Storage and Preparation
Ash Disposal
Annual Cost of Coal and Coal Handling
Annual Cost of Fuel, Fuel Handling and Flue Gas Scrubbing
*Variables Included in the Block are Sulfur Content, Heating Value, Water Content, and Ash Conent.
Area I - Power Plant
Area II - Flue Gas Scrubbing System (Detail is shown in Figs. 2 and 3)
Area III - Coal-Related Operations

Figure 16. General procedure for calculation of common cost factor for add-on scrubbing systems

this area. The input variables are: plant capacity in megawatts, type of coal, and the modified load factor for each boiler from Area II. The input variables included in the type of coal are coal sulfur content, heating value, water content, and ash content. The outputs from this area are sulfur and flue gas flow rates for each boiler at full capacity, load factor of each boiler before the scrubbers are installed, and annual consumption of coal.

Area II contains the calculations to obtain the annual production cost of the scrubbing system. Detailed procedures involved in this portion of the Wellman-Allied process are shown in Figures 16 and 17, respectively.

The cost models for these two processes as derived by the M. W. Kellogg Company have been modified to change the costs of electricity and steam to the cost of additional coal needed and the additional cost of desulfurizing the increased flue gas. Several simultaneous algebraic equations were derived and solved to obtain the additional heat input needed. The increased annual production cost is calculated by using a modified load factor for each boiler.

The outputs from Area II are the modified load factors for each boiler and the total annual production cost for the scrubbing system.

Area III includes cost of coal and its handling. The input variables are mine-mouth costs of coal, coal transportation costs, costs of coal storage and preparation, and costs of ash disposal. The output is the annual cost of coal and coal handling.

The total annual production cost for the scrubbing system obtained from Area II and the annual cost of coal and coal

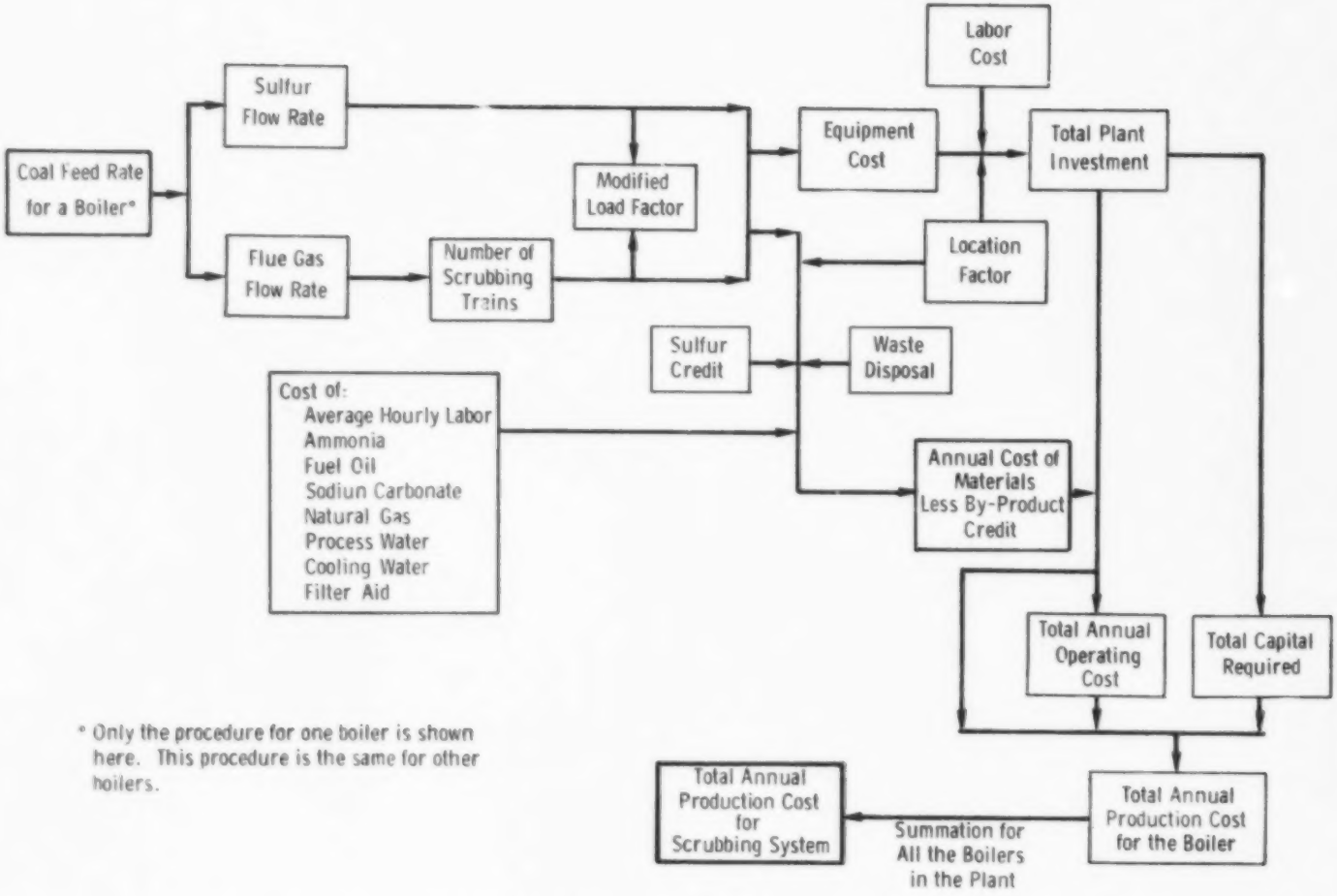


Figure 17. Calculation of annual production cost of Wellman-Allied Process

handling obtained from Area III are then added together to get the annual cost of fuel, fuel handling and flue gas desulfurization.

Discussion - In all the cost calculations for utility power plants, a heat rate of 10,400 Btu/kwh was used to calculate the fuel demand for each boiler regardless of the size and age of the boiler. This heat rate represents an overall cycle efficiency of 32.7%, and is about the average for all utility boilers. If one is looking at the cost for SO_2 abatement for a new and large plant or an old and small plant, this heat rate may not be accurate. However, if the same heat rate is used for comparing all abatement methods, it is believed that the comparison is still valid even at these extreme cases.

Sample Results

Table 9 lists the deterministic input values used in the Wellman-Allied simulation. The state variables were fitted to Weibull distributions; their one and ninety-nine percentile values are tabulated below.

Item	Low value (1%)	High value (99%)
Location factor	0.929	2.10
Percent sulfur in coal	0.141	3.94
Utility plant size (mega-watts)	19.1	2366
Cost of coal	$9.23	$22.23
Transportation distance	453 miles	1607 miles
Industrial boiler size (million Btu)	10.0	2710

Table 9. INPUT VARIABLES, WELLMAN-ALLIED PROCESS

Name	Item	Value
CO	Average Hourly Labor Rate	$ 7.00 Per Hour
CWATER	Cost of Water	$ 0.20 Per K Gal
CDPOSE	Cost of Waste Disposal	$ 3.00 Per Ton
CSULF	Credit for Sulfur By-Product	$ 50.00 Per Ton
HV	Heating Value of Coal	12000. Btu/Lb
FWATER	Fraction of Water in Coal as Received	0.20
FASHRC	Fraction of Ash in Raw Coal as Received	0.08
CNH3	Cost of Ammonia	$ 200.00 Per Ton
CFOIL	Cost of Fuel Oil	$ 0.80 Per MBtu
CELEC	Cost of Electricity	8.00 Mils/Kwhr
CONTIN	Contingency	0.10
CS	Purchased Price of Sodium Carbonate	$ 90.00 Per Ton
CN	Purchased Price of Natural Gas	$ 0.50 MSCF
CH	Purchased Price of Steam	$ 0.50 Per K Lb
CC	Purchased Price of Cooling Water	$ 0.02 Per K Gal
CFA	Purchased Price of Filter Aid	$ 50.00 Per Ton

Table 10 lists sample results for the Wellman-Allied process. The baseline calculation is a simulation performed with all probabilistic inputs being sampled. The remaining rows show the sensitivity of the model to the state variable inputs. Thus "Location Factor High" means that that input was fixed at the value shown in parentheses and all remaining state variables were sampled probabilistically.

Cost Model for Wellman-Allied Process

Nomenclature

GP	Total flue gas to control plant	KCFM (actual)
GT	Total flue gas to each absorber train (maximum value of GT = 500)	KCFM (actual)
NA	Number of absorber trains	
SF	Total sulfur flow in flue gas to control plant	K lbs/hr
S7	Total sulfur flow in flue gas to control unit per train of sulfur-related equipment in absorber and SO_2 regeneration areas (maximum value of S7 = 7)	K lbs/hr
S28	Total sulfur flow in flue gas control unit per equipment train in the purge/make-up and SO_2 reduction areas (maximum value of S28 = 28)	K lbs/hr
N7	Number of trains of sulfur-related equipment in the absorber and SO_2 regeneration areas	
N28	Number of equipment trains in the purge/make-up and SO_2 reduction areas	
E	Major equipment cost (direct material and subcontracts)	$K
M	Field materials costs	$K

Table 10. SIMULATION RESULTS - UTILITY BOILERS

WELLMAN-ALLIED PROCESS (1974 PRICES)

	Average TAC (x 10)	Average cost per megawatt plant capacity	Mils per Kwh
Baseline	$ 32.2	$ 88,300	19.2
Location factor high (2.10)	$ 32.5	$ 89,000	19.4
Location factor low (.929)	$ 32.3	$ 87,700	19.1
% Sulfur in coal high (3.94)	$ 35.4	$ 97,800	20.1
% Sulfur in coal low (0.14)	$ 30.1	$ 80,900	18.1
Power plant size low (19.1)	$ 2.20	$115,000	25.0
Cost of coal high (22.23/ton)	$ 37.8	$102,000	22.2
Cost of coal low (9.23/ton)	$ 27.4	$ 75,900	16.5
Transportation distance low (453 miles)	$ 25.3	$ 70,900	15.4

VALUES FOR 10,000 SIMULATIONS

Nomenclature

L	Field labor costs	
A, S, P	Letters following E, M, L A refers to absorber area S refers to SO_2 regeneration area P refers to purge/make-up area R refers to SO_2 reduction area No letter following refers to total for all area	
IF	Particulate index (IF - 1 if particulates are present in flue gas. IF = 0 if particulates are absent).	
RB	Retrofit difficulty factor of each boiler	
RP	Retrofit difficulty factor of gas-related equipment in the absorber area which is not in parallel trains, i.e., the fuel oil system; assumed to be equal to the highest RFB	
BARC	Bare cost of the control unit	$K
TPI	Total plant investment	$K
TCR	Toal capital required	$K
CONTIN	Contingency	$K
AS	Annual cost of sodium carbonate	$K/yr
AAO	Annual cost of anti-oxidant (amine)	$K/yr
AN	Annual cost of natural gas	$K/yr
AFA	Annual cost of filter aid	$K/yr
AE	Annual cost of electric power	$K/yr
AH	Annual cost of steam	$K/yr
ACW	Annual cost of cooling water	$K/yr
AW	Annual cost of process water	$K/yr

Nomenclature

AF	Annual cost of fuel oil	$K/yr
ASC	Annual sulfur credit	$K/yr
APS	Annual purge solids credit or debit	$K/yr
CS	Purchase price of sodium carbonate	$/ton
CN	Purchase price of natural gas	$/KSCF
CFA	Purchase price of filter aid	$/ton
CE	Purchase (or transfer) price of electricity	mills/kwh
CH	Purchase (or transfer) price of steam	$/K lbs
CCW	Cost of cooling water	$/K gal
CF	Purchase price of fuel oil	$/M Btu
VSC	Unit value of sulfur (negative if credit)	$/long ton
VPS	Unit value of purge solids (negative if credit)	$/ton
TO	Total number of operators	
CO	Unit cost of operating labor	$/hr
LF	Load factor of the power plant	
AOC	Annual net operating cost	$K/yr
TAC	Total annual production cost	$K/yr
F	Location factor	

Capital Cost Model Summary of Equations

$$EA = \sum_{n=1}^{NA} RB\left[726\,(CT/550)^{0.5} + 639\,(GT/550)^{0.9}\right]_n + 119\,RP\,(GP/3300)^{0.5} + \left[133\,(S7/7)^{0.5} + 127\,IF\,(S7/7)^{0.6}\right]N7 \quad \$K$$

$$ES = \left[209\,(S7/7)^{0.5} + 618\,(S7/7)^{0.6} + 157\,(S7/7)^{0.9}\right]N7 \quad \$K$$

$$EP = \left[525\,(S28/28)^{0.5} + 380\,(S28/28)^{0.6} + 86\,(S28/28)^{0.7} + 306\,(S28/28)^{0.8} + 519\,(S28/28)^{0.9}\right]N28 \quad \$K$$

$$ER = 998\,(SF28)^{0.5} + 287\,(SF/28)^{0.6} + 683\,(SF/28)^{0.9} \quad \$K$$

$$M = 0.429\,EA + 0.742\,ES + 0.827\,EP + 0.772\,ER \quad \$K$$

$$L = 0.224\,EA + 0.310\,ES + 0.433\,EP + 0.623\,ER \quad \$K$$

$$BARC = 1.15\,(E+M) + 1.43\,L \cdot F \quad \$K$$

$$TPI = 1.12\,(1.0 + CONTIN)\,BARC \quad \$K$$

$$TCR = 1.15\,TPI + 0.8\,TO \cdot CO\,(1+F) + 0.4\,ANR \quad \$K$$

Operating Cost Model

$$AS = 28.2\,CS \cdot LF\,(SF/28) \quad \$K/yr$$

$$AAO = 0.04\,CAO \cdot LF\,(SF/28) \quad \$K/yr$$

$$AN = 1460\,CN \cdot LF\,(SF/28) \quad \$K/yr$$

$$AFA = 1.24\,CFA \cdot LF \cdot IF\,(GP/3300) \quad \$K/yr$$

$$AE = \left[154\,(GP/3300) + 79\,(SF/28)\right]\,CE \cdot LF \quad \$K/yr$$

$$AH = 5430\,CH \cdot LF\,(SF/28) \quad \$K/yr$$

$$ACW = \left[856\,(GP/3300) + 19{,}900\,(SF/28)\right]\,CCW \cdot LF \quad \$K/yr$$

$$AW = 64\,(SF/28)\,CW \cdot LF \quad \$K/yr$$

$$AF = 1{,}800\,(GP/3300)\,CF \cdot LF \quad \$K/yr$$

ASC	= 95.4 (SF/28) VSC·LF	$K/yr
APS	= 37.3 (SF/28) VPS·LF	$K/yr
ANR	= AS + AAO + AN + AFA + AE + AH + ACW + AW + AF + ASC + APS	$K/yr
AOC	= 0.078 TPI + 2·TO·CO (1+F) + ANR	$K/yr
TAC	= 0.237 TPI + 2.1·TO·CO (1+F) + 1.04 ANR	$K/yr

SECTION X

REFERENCES

1. Shore, D., J. J. O'Donnell, and F. K. Chan. Evaluation of R&D Investment Alternatives for SO_x Air Pollution Control Processes. EPA 650/2-74-098, 1974.

2. North, D. W. Systems Science and Cybernetics. SSC-4 (3), 1968. p. 200.

3. Howard, R. A. Ibid., p. 211.

4. Weibull, W. Fatigue Testing and Analysis of Results. New York, Pergamon Press, 1961.

5. U.S. Department of Labor. Monthly Labor Review. November 1974.

6. U.S. Department of Commerce. Survey of Current Business. November 1974. p. 109

7. U.S. Department of Labor. Monthly Labor Review. September 1974. p. 85.

8. U.S. Department of Labor. The U.S. Economy in 1985: A Summary of BLS Projections. 1974. p. 54.

9. Continental Oil Company. Coal and Energy Shortage. (Presented to Security Analysts. December 1973) p. 19.

10. Ibid., p. 24.

11. Moody's Transportation Manual. 1974. p. 20.

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12. National Coal Association. Steam Electric Plants Factors. 1973. p. 55.

13. U.S. Department of Labor. Monthly Labor Review. August 1974. p. 70.

14. Coal and Energy Shortage. Op. Cit., p. 18.

15. The U.S. Economy in 1985; A Summary of BLS Projections. Op. Cit., p. 37.